UCRL- 92528
PREPRINT

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This Paper Was Prepared for Submittal to
11th IEEE Symposium on Engineering Problems
of Fusion Research
Austin, TX
November 18-22, 1985

October 1985

Lawrence Livermore National Laboratory

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Abstract

The Lawrence Livermore National Laboratory is evaluating the engineering feasibility and economics of a superconducting ignition tokamak. Two major operational requirements had to be satisfied: 1) the conductive heat leak to the refrigerated structure had to be minimized, and 2) assembly and maintenance of the entire experiment had to be possible with remotely operated tools. The middle poloidal "push coil" must have many annular disks to transfer the TF-coil inward force to the post without crushing superconductor. The toppling moment on the TF-coil vertical legs is huge. A method of keying together the TF-coil cases has been developed. This forms an integrated structure that resists torque. The joining technique permits linear motion for simple assembly/disassembly. The toppling moment on the outer vertical legs of the TF coils is very large. To react that moment and avoid great coil-case bulk, we have developed a method that allows the PF coil support structure to assist the TF case structure. Finite element techniques were used to determine the ability of the coil case and conductor to react the magnetic loads. The entire cold-coil structure is mounted on a circular plate that is suspended by several large tension rods, similar to the MFTF-B yin-yang support rods. The vacuum vessel is all at room temperature and is configured like a bell jar with sixteen side doors, one for each shield module.

TIBER - The Mechanical Structure

Fundamental Considerations for Tokamaks

All fusion machines using the tokamak geometry require that special attention be payed to the stress generated in the toroidal field (TF) coil's inboard legs and in the center post, which supports all TF coils. The magnetic loading on TF coils develops a large overturning moment. At the inboard legs the sense of this moment is opposite to that of the overturning moment of the outboard legs. In addition to the overturning moments, a huge thrust against the center post results from the interaction between current direction and the toroidal magnetic field. Figures 1a, 1b, 1c, and 1d show one of the TF coils. These figures illustrate the sense and magnitude of the magnetic force components: x, z, and azimuthal. The azimuthal component produces the large overturning moments.

The Cold Island

This tokamak employs superconductor for both TF coils and all poloidal field (PF) coils including the center post coils. Because temperatures below 5 K are necessary for operation of all the coils, it is essential that all coil cases be thermally isolated from the tokamak's vacuum enclosure.

It is not practical to absorb the large coil forces by bracing each coil case against warm structural supports because the heat flow path thus introduced would overwhelm any 5 K refrigeration plant of reasonable cost. Our solution is to develop a "cold island" of structure and magnets that is capable of holding the coils in an undeformed condition while minimizing the heat transfer to the "island" from the environment. Figure 1d shows the cold components and their operational, geometric relationship. The "island" consists of

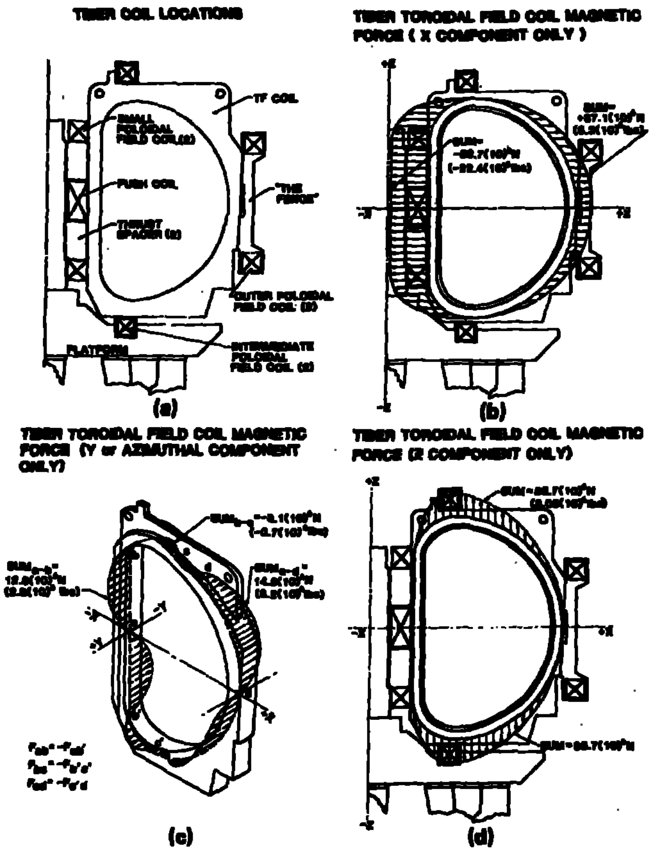

Fig. 1. Magnetic force components of TF coil.

1. A large plate-like platform with a rigidly mounted center post and eight legs (Fig. 2).

2. The small-diameter PF coils and the "push-coil" between them with appropriate spacers. These three coils fit over the center post.

3. The sixteen TF coils.

4. The large-diameter PF coils and their connecting structure. These all attach to the outboard vertical legs of the TF coils.

5. The intermediate-diameter PF coils at the top and bottom of the coil array.

Extending below the plate-like disk are eight pedestal legs; each with an attachment point for a turnbuckle hanger at the very bottom of the leg.

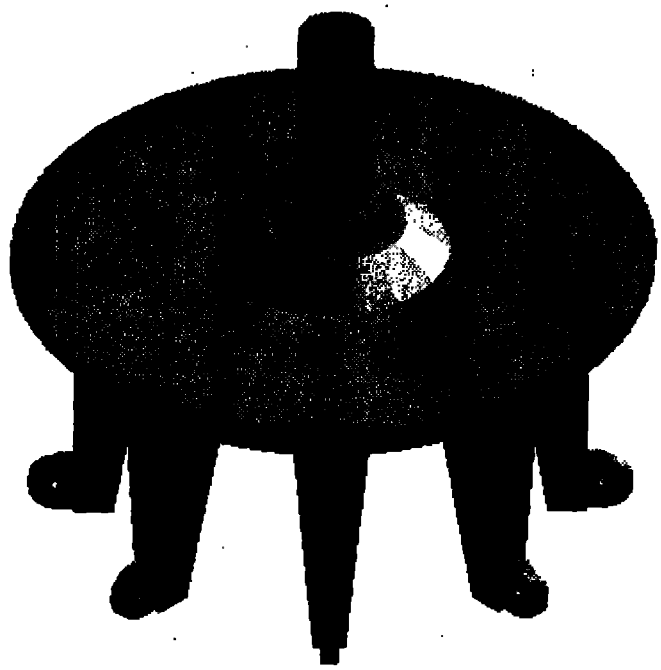

Fig. 2. Coil support platform for "cold island" in TIBER.

Eight rods, each 2.5 m long and adjusted to share the load, suspend the "cold island." The pedestal legs extend into a basement, whose walls are warm, and form the lower portion of the vacuum containment. These eight rods serve as the primary structural connection to the environment. Earthquake stability is provided by snubber rods in a horizontal plane.

PF Coil Removal

Establishment of this "cold island" creates a problem with potentially serious implications for assembly and maintenance. One outer PF-coil plane is 1.5 m above the plasma centerline and the other is the same distance below. PF coils trap the TF coils and all coil shield segments, preventing radial motion. The two large PF coils must be moved to allow assembly and coil or shield replacement. We have joined these PF coils by a heavy structural ring so the assembly forms a "fence" around the TF coils. Vital to its function is the tapered inside bore of the "fence." When in an operational position, this "fence" is engaged with the coil case of each of the sixteen TF coils. Several large tapered dowels (driven by gear-motor assemblies mounted on the "fence") engage both the upper and lower halves of the TF coils. These large dowels have two purposes. First, they support the weight of the "fence" as it girdles the "cold island." Second, they transmit the outer-leg overturning moment to that portion of the "fence" that separates the large PF coils. This applies a shear load to the center of the "fence."

When the "fence" must be removed, eight 18-inch-diameter support rods move up from the machine support area beneath the tokamak. These rods take up the "fence" weight. The tapered dowels are then extracted by their motors. Coil current connections and cryogenic plumbing lines are disengaged. The "fence" assembly is next lowered hydraulically into an annular storage pit under the tokamak. The taper allows immediate disengagement of the "fence" from the TF coil cases as translation to storage begins. Figure 3 shows "the fence" in both locations.

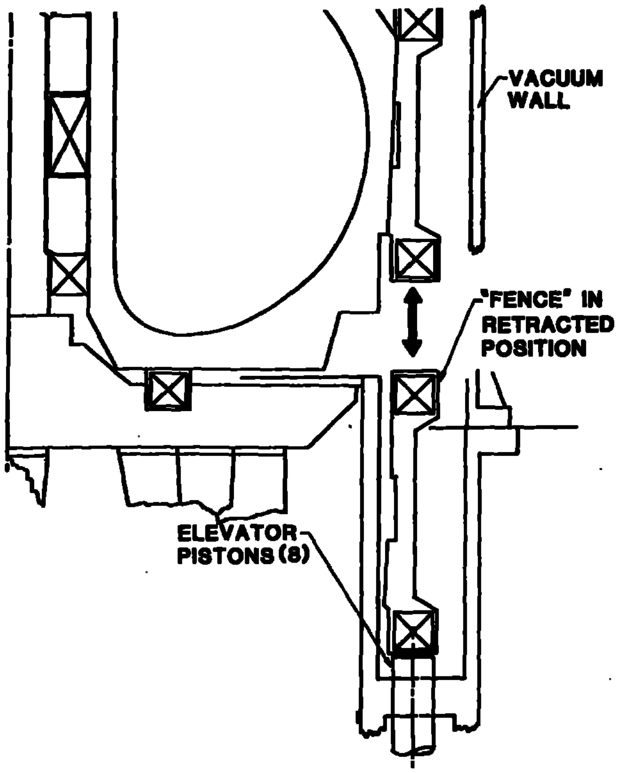

Fig. 3. TIBER outer poloidal-field coil retraction method.

Overturning Moment on Inboard Legs

A structure could be designed to span the radial distance from the inboard legs to the outer PF coils. Such a horizontal plate would transmit the inboard leg's azimuthal forces to a structure attached to the PF coil assembly (the "fence"). Hence the large torque would not be transmitted through the TF-coil upper case. If the upper case structure had to transmit that load, its mass and dimensions would impair access of the neutron shield. As described later, that shield must be assembled radially between the TF coils. We have tried to limit the TF-coil-case width to about 0.5 meters.

The base of the machine acts as the horizontal plate transmitting the TF-coil overturning moments on the bottom half of the tokamak. A similar structure might span the top of the machine. It would be massive and would have to be removed to allow TF-coil replacement or replacement of the intermediate PF coil directly above the plasma.

The inboard legs of the sixteen TF coils can be mechanically joined in such a way as to transmit vertical shear between adjacent coil cases. By interlocking this closely spaced group of coil cases, a cylinder is formed with a very large polar moment of inertia. Preliminary analysis revealed that, with about 3 cm of coil-case thickness both inboard and outboard of the vertical leg of the TF-conductor bundle, the "cylindrical" structure could restrain the magnetic forces. The predominant force has two major components. A large radial-force component directed inwardly toward the center post creates a crushing pressure of about 9300 psi at the outside surface of the push coil and its adjacent spacer rings. A comparably large force tries to rotate the "cylinder" about the center post. The sense of this force changes so that the lower half of the "cylinder" experiences a torque opposite to that experienced by the upper half.

The latter approach is believed to be the more economical design. Maintenance and coil replacement are much more easily accomplished without a torque structure blocking crane access to TF coils and shield segments. Our work so far indicates that the joining of adjacent TF-coil inboard legs will result in a good torque-reacting structure. In a later section of this report we describe the means of locking together adjacent coil cases.

The analysis of this complex structure and equally complex set of magnetic loads must use finite-element analytic techniques. The results presented here break the structure into the number of elements that could be dealt with by available time and manpower. The conclusions must be regarded as tentative until a more elaborate and detailed element array can be generated and analyzed by the GEMENI code.[1]

In order to perform the finite-element stress analysis, it is necessary to know the magnetic loads on the several coils. The code employed is EFFI,[1] which was developed at LLNL and has been refined and used extensively for the past decade at magnetic fusion research laboratories throughout the United States. The curved sections of the TF coils were broken into chordal elements that coincide with the node locations used in the GEMENI[2] code.

The Upper Coil Case

Because of symmetry about the horizontal midplane, the sum of the torques for both structures reduces to zero. But the top and bottom legs of the TF coils also experience substantial magnetic loading. The upper leg might be visualized as a beam spanning the gap between the inboard structure (described before as the "cylinder") and the outboard structure (called the "fence"). We have analyzed the hollow box beam formed by the coil case. The end conditions for that beam were described to the GEMENI code as spring constants for the three translational degrees of freedom of each node. The only nodes for which spring constants needed definition were those that describe the two end planes. The box beam so analyzed is curved and is about 2.3 meters arc length. For ease of assembly, we maintained the overall coil-case width at a constant value and instead increased the outside wall's thickness because no space restrictions existed there.

The Shield and Its Installation

Due to the large amount of energy absorbed by the shield it must be warm in operation and be actively cooled, probably by water. This shield must be inside the bore of the TF coils, which are at 5 K. The weight of the 900-tonne shield must be born by the "cold island" support pedestal. Radiation shields between the neutron shield and the superconducting magnet cases are essential. Because the neutron shield mass must be carried on the top surface of the pedestal plate, a very good load-bearing material must provide superior thermal insulation between the warm shield and the "cold island." The load must distribute to an annular ring of about 4-m outside radius and 3-m inside radius. Only about two-thirds of that area is available for shield support due to the presence of the TF-coil bases. A material capable of supporting 80 psi while retaining exceptionally low thermal conductivity will be required. Such materials exist, but further development will reduce their conductivity and decrease the size of the helium-liquefaction facility required. One example is the LI-900 insulation developed for the NASA Space Shuttle. At its lowest density of 5 lb per cubic foot it supports 40 psi. It is also available in densities up to 20 lb per cubic foot.

The shield consists of 32 major segments. The largest of these is a rectangular prism with a large D-shaped hole through it. Sixteen of these segments slide in between the TF-coil outboard legs. These segments do not protect the outboard legs of the TF coils. Each TF coil must have within its bore, adjacent to the outboard leg, a lunar-shaped segment of neutron shield. Figure 4 illustrates the two types of neutron shield segments and the way they fit together.

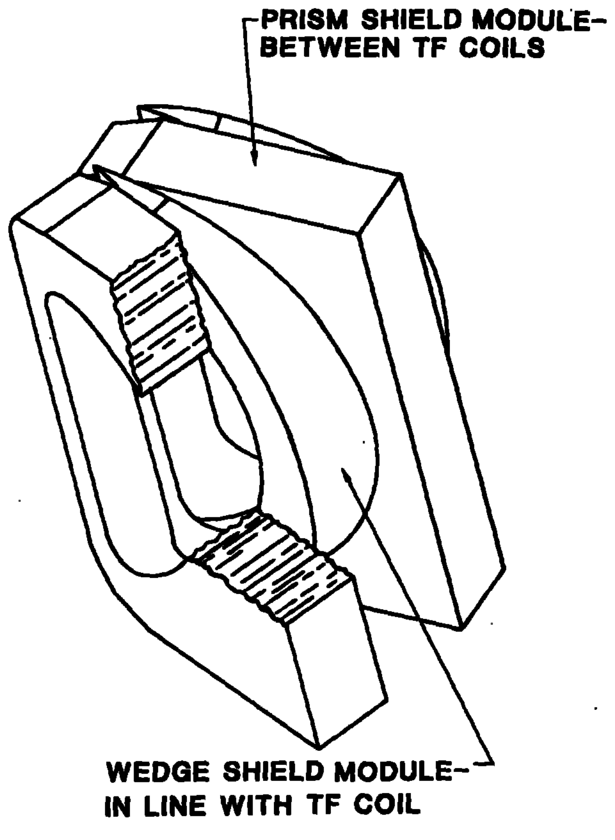

Fig. 4. Relationship between the two shield modules required for TIBER.

During assembly it will be necessary to first install the smaller (lunar) segments. Their weight can be supported by attaching them to the TF coil through long, low-conductivity support rods. After installing the lunar segments, the larger prisms can then be moved in radially.

The Vacuum Enclosure

The tokamak itself sits on the pedestal plate slightly above the containment building's main service floor. A stainless steel "bell jar" fits over the entire machine to form the vacuum boundary above floor level. This structure is best described as a cylindrical wall with sixteen, equally spaced, large access doors. Closing the top end of this 13-m-diameter cylinder is a domed cover. This cover must be removed to install or replace a TF coil.

The sixteen doors are spaced exactly between adjacent TF coils. The radial movement of the shield segments is through these doors. The TF coils will have to move radially in order to disengage from the shear connections joining their inboard legs. The bell jar is large enough to permit about 1 m of TF coil radial motion. A TF coil is then removed vertically by crane.

The radially inward force on the inboard TF-coil leg creates a uniform pressure of 9,270 psi on the small PF coils, the "push coil," and the spacer rings.

These coils and spacer rings must be dimensioned and shimmed to make a close fit on the post. This eliminates induced shear and limits the radial stress in the post, as well as in the coil cases and spacer rings, to 9,270 psi. If the post were not present, the tangential stress at the coil and spacer bores would be 25,600 psi and the induced shear would be 12,800 psi.

Torque on Inboard Legs

Calculations were made to predict the approximate shear in the TF-coil case at the tokamak midplane. The calculations neglect any restraint from the top/bottom TF-coil case, so the stress calculated is higher than one would obtain if the whole system could be included. The total magnetic torque is 2.04×10^{9} in.-lb. The shear stress at the machine midplane was shown to be 50,320 psi, a reasonable stress level for type 304 LN steel at 4.5 K.

GEMENI uses the Von Mises criteria for failure (also known as the "maximum distortion energy theory"), which has gained general acceptance as being applicable to both brittle and ductile materials. The effective stress (S_e) calculated for this complex array of TF-coil legs, radial spacers, and post is 88,150 psi, which is higher than the 66,667 psi usually used for 304 LN stainless steel at a temperature of 4.5 K. We intentionally use the larger number to account for metallurgical developments that are inevitable between now and the year 1990 or beyond, when TIBER might actually be constructed. If such improvements are late in arriving, we have space available on the side of the coil cases facing plasma, i.e., the bore of the TF coils, to thicken the coil cases and thereby reduce the effective stress.

A small penalty is paid for thicker coil cases. The amount of structure at 4.5 K increases, and because that particular structure acts as part of the superconductor's neutron shield, the heat load on the cryogenic system will increase as much as 10%. This is deemed an acceptable price.

The model we used for GEMENI is shown in Fig. 5. This was repeated sixteen times to form a body of revolution about the axis. The distribution of TF-coil forces causes considerable variation in effective

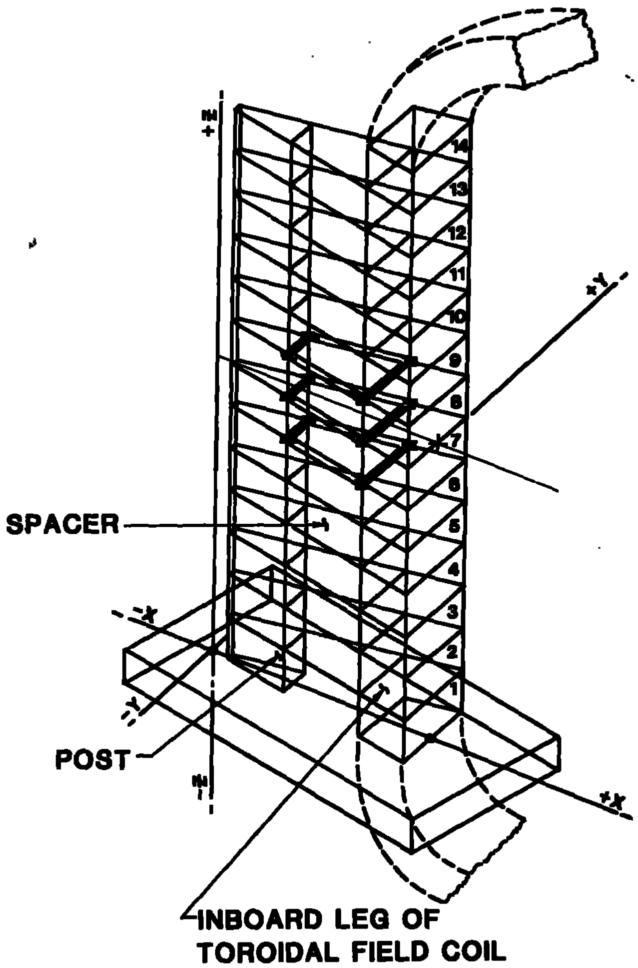

Fig. 5. Segment identification used in finite-element stress analysis.

stress along the length of the inboard leg of the TF coil. We illustrate that variation in Fig. 6, where only Von Mises effective stresses are plotted. The reason that two values (S_{e+} and S_{e-}) are shown is that calculations for both sides of the plate are made (i.e., the side facing the superconductor and the side visible to an observer). The difference is small. We have plotted not only values for the TF-coil case, but also values for the post and for the push coil "washers." The latter values are seen to be lower than that for the case stress. The S_e of 77,500 psi for the push coil "washers" indicates that the number and thickness assumed are nearly optimum. There would be nine discs, each 1 cm thick and equally spaced along the length of the push coil.

TF-Coil Shear Connections

The greatest challenge in assembling the TF coils is to join them near the center post such that shear stresses can be transmitted between adjacent coil cases. The tendency to "overturn" is thus resisted. Figure 7 shows two methods for locking together adjacent coil cases. For each method, the viewer is looking radially inward toward the center post, between two TF coils. It is easily seen that to put the leg in static equilibrium, large shear forces must

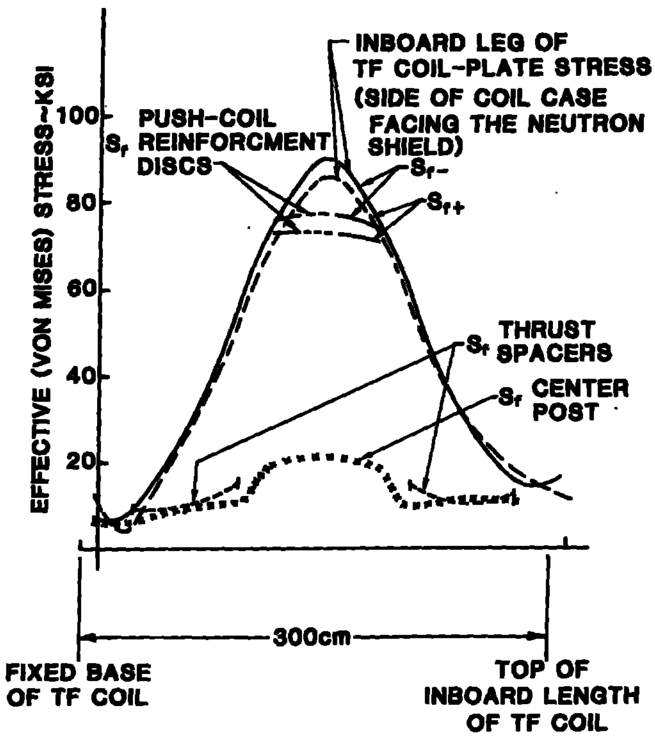

Fig. 6. Von Mises stress at important points in TF coil, spacer, push coil, and center post.

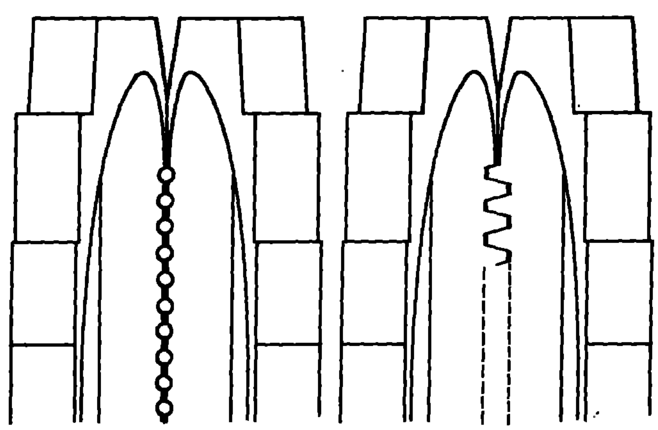

Fig. 7. Two methods for locking the TF coils together.

be exerted on the vertical sides of the coil case. One solution that also helps the reader visualize this requirement is to put rack gear teeth on adjacent faces of neighboring coil cases. These teeth would prohibit those surfaces from sliding as the individual coils attempted to topple (overturn). Although we considered such a toothed surface, we concluded that the machining accuracy required on large steel assemblies would be too costly. Instead we suggest an assembly that produces a similar effect but that is much simpler to manufacture and assemble.

In our proposal, a number of pilot semicircular grooves would be machined in the case sides. The centerlines of the grooves should point toward the center line of the post after all the TF coils are in position. Adjacent case sides would have mirror-image grooves and, if alignment were perfect, a pin could be inserted in the "hole" so formed. As this level of precision would certainly be too costly and probably unattainable, we would instead rough-machine the grooves to about 75% of their final diameter. After locating the TF coils against the post, the holes would be enlarged and reamed using the small and mismatched grooves as a "pilot holes". Calculations of shear indicate that 20 one-inch diameter dowels at each case interface would provide the needed balancing shear force at a stress level of 48,000 psi. Since this is the only loading on the dowels, the stress level should be tolerable. The dowels can not be much larger without breaking through the case wall.

These dowel "teeth" would be machined by a special tool with the coils in final position. The dowels would have to protrude to allow them to be gripped for removal. Some consideration has been given to using tapered pins in tapered, reamed holes because the removal problem would be greatly simplified.

Torque on Center Post

The total twist produced by the magnetic forces acting on the column formed by the sixteen legs of the TF coils is about 0.2°. If the center post were somehow connected to the TF-coil legs, the post would also twist 0.2°. A simple calculation shows that the torsional shear stress produced in the post is 10,500 psi and the torque related to the angular deformation is only 6% of the torque being resisted! We conclude that any attempt to make the center post share the torque load is unjustifiable.

Combined Stresses in the Upper TF-Coil Case

The upper TF coil case makes a bridge-like connection between the inboard-leg and center-post assembly and the outer PF-coil assembly. A similar geometry exists at the bottom of the TF coils, where the case is radially deeper and the platform structure further reinforces the coil case. We therefore analyzed only the upper "bridge" for this report.

In order to withstand the bending loads exerted by the magnetic forces, it was necessary to add considerable cross-sectional area to the coil case in this "bridge" structure. The case was deepened radially to nearly double its usual dimension, and material was added to the back of the conductor bundle (as viewed from the plasma). Figure 8 shows the cross section used.

The GEMENI code required the end nodes of this "bridge" structure to have spring loads applied to them. These spring constants must be representative of the structure to which the "bridge" is joined. At this stage of design we had to approximate the area and length of material joined to particular end nodes. Using estimated areas and lengths it is possible, with known values for the elastic modulus, to calculate equivalent spring constants in the local orthogonal coordinate system. It is necessary to estimate boundary conditions only when just a portion of the structure is being defined.

The highest stressed region is along the case surface facing the plasma, near the connection to the side walls. We find the maximum effective stress to be 88,150 psi on the surface of the plate.

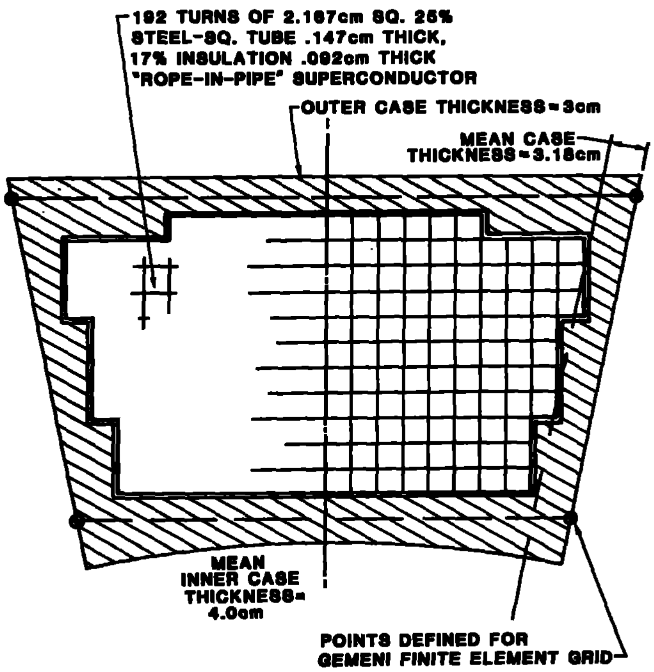

Fig. 8. Toroidal-field-coil inboard leg showing conductor location and case walls.

The contribution of the steel present within the conductor has not been taken into account. This steel will probably be in the form of hollow square tubes containing the superconductor and providing the flow area for forced-flow liquid helium. (This is commonly referred to as the "rope-in-a-pipe" design.) The effect of this additional steel is to increase the moment of inertia of the typical coil case cross section by about 15%, further reducing the operating stress level. Figure 8 shows the TF-coil cross section of the inboard leg.

Combined Stress in the Large PF-Coil Support Structure

We have previously described how a cylindrical structure (dubbed the "fence") joins the two outer PF coils. The "fence" is used to resist the overturning torque on the outer legs of the TF coils. It also integrates an assembly that is lowered into a parked position for TF coil or neutron shield removal.

Loads on the structure arise from two major sources: first, from the magnetic forces on the two PF coils; and second, from the magnetic force on the outer legs of the TF coils. The TF-coil cases are not very wide. In this simple analysis we neglect their strength to resist overturning moments. A more complete analysis using finite-element techniques will show the load sharing capability of these TF-coil cases.

If one assumes a wall thickness for the "fence" of six inches, the various midplane stresses can be calculated. Table 1 shows the results of these calculations.

Table 1. Midplane stress in outer PF-coil assembly.

Circumferential tension due to burst forces	36,610 psi
Axial tension	7,318 psi
Torsional shear	10,521 psi

The Von Mises stress[3], often used as a failure criteria, is 33,556 psi. This is a conservative value for type 304 LN stainless steel at the operating temperature of 4.5 K.

Acknowledgment

This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

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[2] R. C. Murray, GEMENI—A Computer Program for Two- and Three-Dimensional Linear Static and Seismic Structural Analysis, Lawrence Livermore National Laboratory, Livermore, CA, UCID-20338, 1984.

[3] Von Mises stress =

$$S^2_{max} - S_{max}\, S_{min} + S^2_{min}$$

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